

Department of Civil, Environmental and Architectural Engineering – DICEA Via F. Marzolo 9, 35131 – Padua, Italy. www.dicea.unipd.it

Assessment and improvement of structural safety under seismic actions of existing constructions: Historic Buildings and R.C. Structures. SEMINAR

R.C. STRUCTURES:

INVESTIGATION METHODOLOGIES AND TECHNIQUES: INSPECTIONS, SURVEYS, IN-SITU AND LABORATORY TESTS, MONITORING

Prof. Eng. Claudio Modena

claudio.modena@dicea.unipd.it

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ועדת ההיטי הבין-משרדית להיערכות לרעידות אדמה National Steering Committee for Earthquake Preparedness

THE KNOWLEDGE PROCESS



EUROCODE 8: DESIGN OF STRUCTURES FOR EARTHQUAKE RESISTANCE PART 3: ASSESSMENT AND RETROFITTING OF BUILDINGS

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ANNEX A (INFORMATIVE) REINFORCED CONCRETE STRUCTURES



INFORMATION FOR STRUCTURAL ASSESSMENT

- available documentation specific to the building in question
- relevant generic data sources (e.g. contemporary codes and standards)
- field investigations
- in-situ and/or laboratory measurements and tests

cross-checks should be made between the data collected from different

sources to minimise uncertainties



INFORMATION FOR STRUCTURAL ASSESSMENT

REQUIRED INPUT DATA

- Structural system
- Foundations & ground conditions
- Dimensions and cross-sectional properties of the building elements
- Mechanical properties and condition of materials
- 💻 Seismic design criteria used
- Present and/or the planned use of the building
- Re-assessment of imposed actions
 - Present structural damage, if any, including earlier repair measures



- Historic information: original design reports, events occurred, etc...
- **Geometry**: outline and detailed construction drawings, visual survey
- <u>Details</u>: simulated design (based on regulatory documents and state of the practice used at the time of construction), in-situ inspections
- <u>Materials</u>: destructive and non-destructive testing for complementing the information of standards or original design specifications and test

FACTORS WHICH IDENTIFY THE KNOWLEDGE LEVEL

KNOWLEDGE LEVELS

KL1: Limited knowledge - KL2: Normal knowledge – KL3: Full knowledge



A SUMMARY OF THE KNOWLEDGE STEPS

GEOMETRY

DETAILS

HISTORICAL AND CRITICAL ANALYSIS

HISTORY OF BUILDING, CHANGES, PAST EVENTS

historical and archival investigations

GEOMETRY, DETAILS, CRACK PATTERNS AND DEFORMATIONS

- in-situ surveys
- CONNECTIONS, NO. OF REINFORCEMENT BARS, etc.



 MATERIAL PROPERTIES
 •in situ checking

 MECHANICAL CHARACTERISATION OF CONCRETE AND REBARS

 • in-situ and lab testing

KNOWLEDGE LEVEL AND CONFIDENCE FACTORS





INFORMATION FOR STRUCTURAL ASSESSMENT

CONFIDENCE FACTORS

Knowledge Level	Geometry	Structural details	Material properties	Confidence factors
KL1	Structural Survey	Limited in situ checking	Limited inspection and testing	1.35
KL2		Extended and comprehensive in situ checking	Extended inspection and testing	1.20
KL3			Comprehensive inspection and testing	1.00



On site tests on existing structures: the knowledge process

Knowledge Level	Geometry	Details	Materials	Analysis	CF
KL1		Simulated design in accordance with relevant practice <i>and</i> from limited <i>in-</i> <i>situ</i> inspection	Default values in naccordance with standards of the time of construction and from limited in- situ testing	LF- MRS	CF _{RL1}
KL2	From original outline construction drawings with sample visual survey <i>or</i> from full survey	From incomplete original detailed construction drawings with limited <i>in-situ</i> inspection <i>or</i> from extended <i>in- situ</i> inspection	From original design specifications with limited <i>in-situ</i> testing <i>or</i> from extended <i>in-</i> <i>situ</i> testing	All	CF _{KL2}
KL3		From original detailed construction drawings with limited in-situ inspection or from comprehensive	From original test reports with limited in-situ testing or from comprehensive in-situ testing	All	CF _{KL3}

Table 3.1: Knowledge levels and corresponding methods of analysis (LF: Lateral Force procedure, MRS: Modal Response Spectrum analysis) and confidence factors (CF).

NOTE The values ascribed to the confidence factors to be used in a country may be found in its National Annex. The recommended values are $CF_{KLI} = 1,35$, $CF_{KL2} = 1,20$ and $CF_{KL3} = 1,00$.



EN 1998-3: 2005

- 3.5 Confidence factors
- To determine the properties of existing materials to be used in the calculation of the capacity
- When capacity is to be compared with demand for safety verification, the mean values obtained from in-situ tests and from the additional sources of information, shall be divided by the confidence factor, CF, for the appropriate knowledge level
- Different CF can be selected for different materials according to statistical considerations performed on a set of meaningful data for the studied elements and evaluation methods of proven validity





Additional required input data for RC structures

<u>Geometry</u>

- Identification of earthquake-resistant elements
- Floor warping
- Beams, columns and walls geometry
- width of T- beam wings
- eccentricity between beams, columns and walls



<u>Details</u>

- Longitudinal rebars in beams, columns and walls
- □ Stirrups step, diameters and geometry
- Beam column joint details
- □ Longitudinal rebars for M⁻ in T-beams
- Support length and restrains of floors
- Cover thickness
- □ Rebars overlap length

<u>Materials</u>

- □ Concrete compressive strength
- ❑ Yield strength, failure strength and elongation of rebars



- simulated design is a procedure used if technical documents are limited and extended investigations can not be performed
- □ it allows the definition of the amount and layout of reinforcement, both longitudinal and transverse, in all elements participating in the vertical and lateral resistance of the building→ KL1
- □ the design should be carried out based on regulatory documents and state of the practice used at the time of construction



What we need?

- □ the knowledge of the period of construction
- □ find regulatory documents at the time of construction
- □ search renowned manuals commonly used at the time of construction
- □ identify the state of practice used at the time of construction also studying other projects, more complete, of the same period

The main step are:

- 1.<u>identification of the period of construction</u> \rightarrow very important information for the collection of historical data
- 2.<u>identification and study of the structural scheme</u> \rightarrow floors, beams, columns, roofs, etc... and study of their structural role (dead loads, horizontal loads)
- 3. <u>choice of the calculation method</u> \rightarrow in non-seismic areas structures were Gravity Load Design using very simplified structural schemes (columns with only simple axial load, series of beams simply supported, etc...)
- 4. identification of loads \rightarrow dead and live loads relating to the original use



- 5. definition of the amount and layout of reinforcement, both longitudinal and transverse, in all elements participating in the vertical and lateral resistance of the building → if stresses are known design and assessment of rebars can be performed using abaci and tables of the time of construction; concerning materials, in the simulated design values of strength are those of the state of practice at the time of construction
- 6. <u>onsite investigations</u> \rightarrow sampling on similar structural elements to verify the performed rebars design
- 7. review of the simulated design \rightarrow correction of rebars details according to onsite investigation results





ON SITE TESTS ON R.C. STRUCTURES



MATERIAL PROPERTIES

<u>Concrete</u>

□ compression tests until failure on cores to obtain mechanical properties \rightarrow <u>concrete compressive strength</u>

<u>Steel</u>

□ tensile tests until failure on rebars samples → yield strength, failure strength and elongation at failure

Non-destructive tests

□ non-destructive tests of demonstrated reliability are admitted but they can not substitute those destructive → they can be used to integrate results from destructive tests only if calibrated on them



On Site Tests on R.C. Structures

TYPES OF INVESTIGATIONS

- Onsite tests: non-destructive (NDT), medium destructive (MDT), destructive
 (DT)
- □ Laboratory tests on elements onsite sampled (rebar pieces, concrete cores)
- In particular non-destructive tests:
- effective for comparing data
- □ fast, cheap and low invasive
- □ results must be calibrated with data from destructive tests
- most common NDT: Schmidt hammer, covermeter, ultrasonic pulse velocity, pull-out test



WHY PERFORMING TESTS?

- identification and localization of cracks, honeycombings and defects inside the RC structure
- determination of concrete homogeneity
- □ definition of the amount and layout of reinforcement bars
- increasing of the knowledge level after performing a limited number of destructive tests
- modification of the use of the structure
- □ resistance check after load application



SAMPLING

- during the sampling campaign a primary aspect to evaluate is the number and location of points to investigate
- sampling points must represent the whole structure, summarizing structural feature variability
- if the structure is very heterogeneous, investigation accuracy must be increased
- □ a well-defined number of investigations does not exist



SAMPLING

- case-by-case a right compromise between knowledge level, imposed deadline, money and invasiveness need to be reached
- to minimize investigation invasiveness prior NDT or MDT for identifying homogeneous areas are recommended
- a limited number of destructive tests allows to calibrate results from non-destructive and medium destructive tests and to extend them to an higher number of points



SAMPLING LOCALIZATION

- □ sampling needs to be carried out in areas with lower stress concentrations
- □ attention to representativeness of samples
- for example, in columns mechanical characteristics are not equal all along their height (decrease from the bottom to the top), so tests performed in the middle of the height are preferable
- in beams midspan region and areas close to bearing points are not good points for investigations (high values of bending moment and shear)



On site tests on existing structures: the knowledge process

TESTING

- Carbonation depth test
- Local scarification



- Survey of the amount and layout of rebars (caliper and covermeter)
- Sampling of rebar pieces
- Corings
- Schmidt hammer tests, ultrasonic tests, pull-out tests





TESTING

- aggregate characterization
- study of porosity
- definition of compositional ratios
- □ identification of alteration phenomena



Visual analysis



BSE image of secondary gypsum



Study of porosity



Scanner image of a polish surface



COST AND RELIABILITY

Test method	Cost	Execution velocity	Damage	Representativeness	Correlation between concrete strength and measured values
Corings	high	slow	moderate	moderate	excellent
Schmidt hammer	very low	fast	none	info about concrete surface	weak
Ultrasonic	low	fast	none	good – all thickness can be investigated	moderate
Pull-out	moderate	fast	limitated	info about concrete surface	good



SCHMIDT REBOUND HAMMER TEST

<u>Principle</u>: the rebound of an elastic mass depends on the hardness of the

surface against which it hits

standard: UNI 12504-2:2001





Bungey & Millard, 1996

SCHMIDT REBOUND HAMMER TEST

- □ to evaluate concrete homogeneity
- □ to define concrete area with decay phenomena
- to obtain qualitative information about superficial concrete strenght (max 30 mm in depth)
- calibration curve supplied with the hammer correlate rebound distance with surface concrete compressive strength





GENERAL PROCEDURE FOR SCHMIDT HAMMER TEST

- check periodically the instrument using the appropriate anvil and in any case perform few beats before recording readings
- □ make 9-25 readings on a squared area of side = 300 mm
- □ minimum distance between two readings= 25 mm
- □ smooth, clear and dry surface without plaster (abrade the surface)
- □ avoid joints, honeycombings, pores
- letter element thickness > 10 cm, side > 12 cm (min mass of the element)
- □ the average rebound index must be obtained eliminating values very different from the mean value
- □ if over the 20% of all measurements differs from the mean value for more than 6 units, all readings must be eliminated



GENERAL PROCEDURE FOR SCHMIDT HAMMER TEST

Factors which can affect or invalidate results:

- □ position of the mass relative to the vertical \rightarrow it can affect the rebound number due to the action of gravity on the mass in the hammer
- $\Box \text{ <u>concrete</u>} \rightarrow \text{type of coarse aggregate, type of cement}$
- □ <u>structure</u> → surface, size, shape, rigidity and age of the specimen, curing conditions
- □ serviceability state → carbonation (ovestimation up to the 50% of the rebound numbers), moisture conditions (rebound numbers are lower for well-cured dried specimens)



<u>Method</u>: Measurement of the velocity of ultrasonic pulses (a frequency of 50 kHz to 60 kHz is suitable for most common applications) of longitudinal vibrations passing through concrete

the equipment consists essentially of an electrical pulse generator, a pair of transducers, an amplifier and an electronic timing device for measuring the time interval between the initiation of a pulse generated at the transmitting transducer and its arrival at the receiving transducer



- Ultrasonic pulse velocity is linked to concrete elastic modulus which can be correlated with concrete resistance
- □ 3 type of waves are created when the surface of a large solid elastic medium is disturbed by a dynamic or vibratory load:
 - → **superficial** waves (or Rayleigh)
 - →shear waves (or transverse)
 - → compression waves (or longitudinal)



 $V = \sqrt{\frac{E_d K}{\rho}}$

□ relationship between elastic constants and the velocity of an ultrasonic pulse travelling in an **isotropic elastic medium of infinite dimensions**:

K=(1-v)/[(1+v)(1-2v)]

E_d=elastic modulus

ρ=density

v=Poisson coefficient

pulse velocity is not significantly affected by the dimensions of the test specimen, except when one or more of the lateral dimensions is small relative to the wavelength of the pulse



<u>Use</u>

- good acoustical coupling between the concrete surface and the face of the transducer provided by a medium such as petroleum jelly, liquid soap or grease
- □ transducer: usually a cylinder of 50-mm diameter
- □ frequencies as low as 10 kHz may be used for very long concrete path lengths and as high as 1 MHz for mortars and grouts or for short path lengths → $10 \div 40$ kHz for L_{max}=15 m / $60 \div 200$ kHz for L< 50 mm
- \Box calibration using a steel bar with a transit time of the pulse of about 25µs



Transducer arrangment (UNI EN 12504-4: 2005)

It is possible to make measurements of pulse velocity by placing the two transducers on either:

- □ A-opposite faces (direct transmission)
- □ B-adjacent faces (semi-direct transmission)
- □ C-the same face (indirect or surface transmission)





Results (UNI EN 12504-4: 2005)

□ for direct and semi-direct transmission longitudianl pulse velocity is given by:

V=L/T

where

V is the longitudinal pulse velocity

L is the path length

T is the time taken by the pulse to treverse that length


Results (UNI EN 12504-4: 2005)

- □ in indirect transmission path length is not measured → preferable to make a series of measurements with the transducers at different distances apart to eliminate this uncertainty
- □ the transmitting transducer should be placed in contact with the concrete surface at a fixed point *x* and the receiving transducer should be placed at fixed increments x_n along a chosen line on the surface
- transmission times recorded should be plotted as points on a graph showing their relation to the distance separating the transducers



Results (UNI EN 12504-4: 2005)

The slope of the best straight line drawn through the points should be measured and recorded as the mean pulse velocity along the chosen line on

the concrete surface



Key

R is the receiver transducer

T is the transmitter transducer

Figure A.1 — Example of the determination of pulse velocity by indirect (surface) transmission



- ❑ the relationship between elastic modulus and compression strength of concrete comes from an experimental calibration → at least 10 sets composed by 3 concrete samples to fill the widest range of possible strength values and 3 velocity readings for each samples
- □ the correlation curve is the following:

where

- f_c = equivalent cubic strength
- e = base of the natural logarithm
- V = pulse velocity

A and B constants





Factors affecting pulse velocity

- □ concrete properties → aggregate size, grading, type, and content, cement type, water-cement ratio, admixtures, age of concrete
- transducer contact
- temperature of concrete
- moisture and curing condition of concrete
- path length
- □ size and shape of a specimen
- level of stress
- □ presence of reinforcement bars



<u>Benefit</u>

- □ suitable for the study of homogeneity of concrete → the most valid and reliable application because it does not require a correlation with a value of concrete strength → velocity maps
- □ locating areas of honeycombed concrete, internal cracks and voids→ if a pulse comes upon an air-filled crack or a void it will diffract around the defect and the pulse travel time will be greater than that through similar concrete without any defect



<u>Benefit</u>

the depth of an air-filled crack or a void can be estimated by the pulse velocity method



where

X =distance to the transducer from the crack (note that both transducers must be placed equidistant from the crack)

- T_c= transit time around the crack
- T_s=transit time along the surface of the same type of concrete without any crack



<u>Benefit</u>

- \Box strength valuation \rightarrow correlation with samples made in laboratory
- valuation of concrete decay
- elastic modulus valuation
- monitoring of strength evolution during time

TABLE 11.3. CLASSIFICATION OF THE QUALITY OF CONCRETE ON THE BASIS OF PULSE VELOCITY

Longitudinal pulse velocity		Quality of concrete
km/s.10 ³	ft/s	
>4.5	>15	excellent
3.5-4.5	12-15	good
3.0-3.5	10-12	doubtful
2.0-3.0	7-10	poor
<2.0	<7	very poor



<u>Principle</u>: relationship between compressive strength of concrete, rebound hammer number, and ultrasonic pulse velocity for compensating mistakes made using methods individually

- \rightarrow SONic + REBound
- \Box concrete compressive strength f_c is assessed using the following expression:

$$f_c = a \cdot S^b \cdot V^c$$

where

S= rebound hammer number

V= pulse velocity

a, b, c =constants

in technical literature series of specific correlations between the combination of rebound hammer number (*R*) and ultrasonic pulse velocity (*V*) and the compressive strength (*S*) of concretes:

$$\begin{aligned} f_c &= 7.7 \cdot 10^{-11} \cdot S^{1.4} \cdot V^{2.6} & \text{norme RILEM, 1993} \\ f_c &= 6.7 \cdot 10^{-8} \cdot S^{1.246} \cdot V^{1.85} & \text{Gasparik, 1992} \\ f_c &= 1.0 \cdot 10^{-9} \cdot S^{1.058} \cdot V^{2.446} & \text{Di Leo-Pascale, 1994} \\ f_c &= 3.7 \cdot 10^{-7} \cdot S^{1.127} \cdot V^{1.690} & \text{Del Monte et al., 2004} \end{aligned}$$









Vona, 2011



Calibration procedure

- 1. Input data
- \Box compressive strength values f_c from destructive tests (corings)
- □ *S* and *V* values from NON destructive tests (Schmidt hammer tests and ultrasonic pulse velocity method)
- 2. As known f_c , S and V, constants a, b and c of Sonreb curves can be evaluated

to obtain f_c through a linear regression using Excel:

$$f_c = a \cdot S^b \cdot V^c$$

IT ALLOWS TO ESTIMATE RESISTANCE ALSO IN POINTS WHERE

ONLY PND WERE CARRIED OUT



- Calculation method of f_{cm}
- 1. compressive strength values f_c from cores onsite sampled
- 2. definition of a, b and c constants of Sonreb curves through a linear regression using Excel and starting from f_c , S and V values
- 3. calculation of cylindrical strength using Sonreb curves where only nondestructive tests were performed
- 4. calculation of average f_{cm} value as average value of destructive results and values from Sonreb curves



PULL-OUT TEST

<u>Method</u>: the pull-out test measures the force required to pull an embedded metal insert with an enlarged head from a concrete specimen or a structure (UNI EN 12504-3: 2003)

<u>Instrument</u>

- □ embedded metal insert \rightarrow cast-in or device installed afterwards by drilling into the hardened concrete
- extractor (hydraulic jack)
- hydraulic pump
- bearing ring
- Ioad cell





PULL-OUT TEST

Linear relationship between pull-out force and concrete strength:

```
f_F = 1.33 \cdot (F-10)  10 \le F \le 60
```

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Key

F Pull-out force in N in accordance with EN 12504-3

Figure 4 — Basic curve for pull out force test



COVERMETER

<u>Principle</u>: magnetic induction applicable to ferromagnetic materials

- □ used for determining the **location**, sizes and depth of reinforcement
- preliminary test to some other form of testing in which reinforcement
 should be avoided or its nature taken into account, e.g. extraction of cores,
 ultrasonic pulse velocity measurements or near to surface methods
- □ a grid 60 cm x 60 cm must be used









COVERMETER

Limitations

- □ it is very slow and labour intensive
- the results are affected by the presence of more than one reinforcing bar in the test area, by laps, by second layers, by metal tie wires and by bar supports
- □ the method is unsuitable in the case of closely packed bar assemblies
- cover thickness max 50 mm
- the accuracy is reduced if rough or undulating surfaces are present, e.g. exposed aggregate finishes. The effect on the indicated cover will be similar in magnitude to the surface irregularities within the area of the search head





SCARIFICATION

- □ <u>Aim</u>: determining the location, sizes and depth of reinforcement
- testing point is chosen according to location of rebars from covermeter results
- □ hammer or chisel to remove concrete cover
- □ caliper to check bar diameter





<u>CORINGS</u>

<u>Method</u>: taking cylindrical concrete cores using a core drill according to UNI EN

12504-1: 2002

- □ it is the most reliable method to identify onsite concrete compressive strength
- □ it is the most effective method to use for the calibration of data from nondestructive tests
- □ for identifying the presence of deleterious matter in the concrete
- □ for ascertaining the strenght of the concrete for design purposes
- □ for the study of the mix design of concrete
- for determining specific properties of the concrete not attainable by nondestructive methods



On site tests on existing structures: the knowledge process

CORINGS







CORINGS

- prepare the ends of cores for compression tests in accordance with UNI EN 12390-3
- ☐ final concrete compressive strength of cores can be affected by numerous factors →it should differ from samples prepared during the casting







<u>CORINGS</u>

Cores diameter

- \Box generally it varies in the range 75 \div 150 mm
- \Box always core diameter $d \ge 3$ maximum aggregate size
- □ according to the test (compression or determination of elastic modulus) core height *h* can vary from d=h to $d \ge 2.5h$
- final concrete compressive strength of cores can be affected by
 honeycomings, rebars, vibrations, drilling direction (if perpendicular to the
 casting, decreasing between 5÷ 8% for concrete of grade 20/25),
 location(resistance decrease from the bottom ti the top), presence of
 humidity(decreasing up to15% of the final strength)



On site tests on existing structures: the knowledge process

<u>CORINGS</u>	EUROPEAN STANDARD NORME EUROPÉENNE	EN 13791			
	EUROPÄISCHE NORM	January 2007			
	ICS 91.080.40				
	E	nglish Version			
	Assessment of in-situ compressive strength in structures and precast concrete components				
	Evaluation de la résistance à la compression du béton en place dans les structures et les élèments préfabriqués	Bewertung der Druckfestigkeit von Beton in Bauwerken oder in Bauwerksteilen			
	This European Standard was approved by CEN on 10 November 2006.				
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A.3.2 Length/diameter ratio .

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On site tests on existing structures: the knowledge process



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7 Assessment of characteristic in-situ compressive strength by testing of cores

7.1 Specimens

Cores shall be taken, examined and prepared in accordance with EN 12504-1 and tested in accordance with EN 12390-3. Except for where it is not feasible, cores shall be exposed to a laboratory atmosphere for at least 3 days prior to testing

NOTE 1 For factors influencing the core strength, see Annex A.

NOTE 2 If for practical reasons 3 days of exposure is not feasible, record the period of exposure, if any. The influence of this deviation from standard procedure should be evaluated.

Where the in-situ strength is determined from cores:

- testing a core with equal length and a nominal diameter of 100 mm gives a strength value equivalent to the strength value of a 150 mm cube manufactured and cured under the same conditions;
- testing a core with a nominal diameter at least 100 mm and not larger than 150 mm and with a length to diameter ratio equal to 2,0 gives a strength value equivalent to the strength value of a 150 mm by 300 mm cylinder manufactured and cured under the same conditions:
- the transposition of the test results from cores with diameters from 50 mm up to 150 mm and other length to diameter ratios shall be based on conversion factors of established suitability.

NOTE 3 Conversion factors of established suitability for other specimen sizes and length to diameter ratios may be given in provisions valid in the place of use.

Normally the core result should not be modified to take account of the direction of drilling unless required by provisions valid in pace of use or required by the project specification.

7.2 Number of test specimens

The number of cores to be taken from one test region shall be determined by the volume of concrete involved and the purpose for the testing of cores. Each test location comprises one core.

For assessment of in-situ compressive strength for statistical and safety reasons, as many cores as are practicable should be used.

An assessment of in-situ compressive strength for a particular test region shall be based on at least 3 cores.

Consideration shall be given to any structural implications resulting from taking cores, see EN 12504-1.

NOTE The number of specimens identified above relates to cores with a nominal diameter of at least 100 mm. The number of cores should be increased when the nominal diameter is less than 100 mm, see A.3.1.

7.3 Assessment

7.3.1 General

In-situ characteristic compressive strength is assessed using either approach A in 7.3.2 or approach B in 7.3.3.

Approach A applies where at least 15 cores are available. Approach B applies where 3 to 14 cores are available. The applicability of the two approaches to the assessment of the strength of concrete in existing structures, about which there is no prior knowledge, may be defined in the place of use.



The estimated in-situ characteristic strength of the test region is the lower value of:

$$s_{s,\mu} = f_{m(\mu),\mu} - k_2 \times s$$
 (1)

OF

f

$$f_{\text{skin}} = f_{\text{islowed}} + 4$$
 (2)

where

- 5 is the standard deviation of the test results or 2,0 N/mm², whichever is the higher value,
- ks is given in national provisions or, if no value is given, taken as 1.48.

The strength class is obtained from Table 1 using the estimated in-situ characteristic strength

NOTE 1 The estimate of characteristic strength using the lowest core result should reflect the confidence that the lowest core result represents the lowest strength in the structure or component under consideration.

NOTE 2 Where the distribution of the core strength appears to come from two populations, the region may be split into two test regions







The estimated in-situ characteristic strength of the test region is the lower value of:

$$f_{ck,sa} = f_{m(n),sa} - k$$
 (3)

or

$$f_{ck,is} = f_{is,lowest} + 4$$
 (4)

The margin k depends on the number n of test results and the appropriate value is selected from Table 2

Table 2 - Margin k associated with small numbers of test results

1	n	k	
Ĩ	10 to 14	5	
	7 to 9	6	
	3 to 6	7	

Because of the uncertainty associated with small numbers of test results and the need to provide the same NOTE level of reliability, this approach gives estimates of characteristic strengths that are generally lower than those obtained with more test results. Where these estimates of in-situ characteristic strength are judged to be too conservative, it is recommended that more cores are taken or a combined technique approach, see 8.4, is used to obtain more test results. For this reason, this approach should not be used in cases of dispute over the quality of concrete based on standard test data, see clause 9 for details of a suitable approach.



CARBONATION DEPTH - UNI 9944/1992

<u>**Principle</u>**: Carbonation of concrete occurs when the carbon dioxide, in the atmosphere in the presence of moisture, reacts with hydrated cement minerals to produce carbonates, e.g. calcium carbonate</u>

- □ the carbonation process is also called **depassivation**
- it is a slow process→ the time required for carbonation can be estimated knowing the concrete grade → the greater is the concrete strength, the slower is the phenomenon of carbonation
- \Box carbonation implies a pH decreasing \rightarrow concrete **pH** becames acid (<12.5)
- \Box alkaline environment which protect rebars disappears \rightarrow corrosion



CARBONATION DEPTH - UNI 9944/1992

- spraying a freshly exposed surface of the concrete with a 1% phenolphthalein solution (core just sampled or as soon as the execution of the compression test)
- □ the calcium hydroxide is coloured pink
- □ the carbonated portion is uncoloured
- test can be performed on the dust from drilling the concrete element









TENSILE TESTS ON REBARS

<u>Aim</u>: evaluation of mechanial properties of reinforcement bars

- on site sampling of rebar pieces
- results:
- -yield strength
- -failure strength
- -failure elongation





<u>Principle</u>: The intensity of a beam of X rays or gamma rays suffers a loss of intensity while passing through a material \rightarrow it depends on the quality of radiation, the density of the material and the thickness traversed





IAEA, 2002



<u>Benefit</u>

- □ locate the position of reinforcement bar in reinforced concrete
- estimates of bar diameter and depth below the surface
- □ revealing the presence of voids, cracks and foreign materials
- □ the presence or absence of grouting in post tensioned construction
- variations in the density of the concrete.





Limitations

- \Box need to re-elaborate images \rightarrow collimation, filtering, etc...
- □ interpretation of concrete radiographs is difficult → no standardized terminology for imperfections and no standardized acceptance criteria
- more used in laboratory, rather than on site
- the technique is possible only when it is possible to have access, at least, two sides of the structure

On site tests on existing structures: the knowledge process

RADIOGRAPHIC TESTING

Technique	Advantages	Limitations
All radiography techniques		Expensive Require skilled operators Require license to operate Require radiation safety program Thin cracks or planar defects perpendicular to radiation beam may be difficult to detect
X-ray	Useful for examining internal macrostructure, e.g., steel location and voids, or microstructure, e.g., steel location and voids, or microstructure Fast View through concrete up to 18 in. (0.5 m) thick View through concrete up to 3 ft (1 m) thick Minimal shielding Energy adjustable for different applications	Primarily a research tool Very expensive initially Potential high voltage hazard
Gamma ray	Useful for examining internal macrostructure, e.g., steel location and voids, or microstructure More portable than X-ray Less expensive than X-ray No electrical power required	View through concrete up to 18 in. (0.5 m) thick Long exposure times
Neutron	Useful for examining microstructure	Primarily a research tool Very expensive initially Little advantage over other radiography methods for most applications on concrete

Handbook on nondestructive testing on concrete, 2004



BS1881 Part 205:1986 Testing Concrete - Recommendations for the Radiography of Concrete"

 \Box radiation sources \rightarrow according to concrete thickness

Source	Approximate concrete thickness	
	Minimum	Maximum
Co-60	125 mm	500 mm
Ir-192	25 mm	250 mm
Linac, `18 MeV X rays	500 mm	1600 mm

- □ type of film and overlap of film
- □ lead intensifying screens
- □ calculation of geometric unsharpness and source-to-film distance
- □ calculation of exposure time
- alignment of the beam
- □ image quality



INFRARED TERMOGRAPHY

Principle: According to the fundamental Law of Planck all objects above

absolute zero emit infrared radiation

- \Box <u>active</u> \rightarrow forced heating to the surfaces analyzed are applied
- \Box <u>passive</u> \rightarrow analyses the radiation of a surface during thermal cycles
- the thermograms taken with an infrared camera measure the temperature distribution at the surface of the object at the time of the test
- □ the temperatures measured are influenced by three factors:
- ightarrow subsurface configuration
- \rightarrow surface condition
- \rightarrow environment



On site tests on existing structures: the knowledge process

INFRARED TERMOGRAPHY

Subsurface configuration

- □ the detectability of any internal structure such as voids, delaminations or layer thicknesses depends on the physical properties of the materials of the test object → heat capacity, heat conductivity, density, emissivity
- if the temperature changes on the surface there is a delay before the effect of this change occurs below where a defect such as a void occurs





INFRARED TERMOGRAPHY

Surface condition

has a profound effect upon the ability of the surface to transfer energy by radiation (emissivity)

- **rough** concrete may have an emissivity of 0.95
- □ shiny metal may have an emissivity of 0.05





INFRARED TERMOGRAPHY

Environment \rightarrow when solar radiation would produce the most rapid heating or

cooling of the concrete surface

- \Box solar radiation
- cloud cover
- \Box ambient temperature(> 0° C)
- □ wind speed(< 25 km/h)
- □ surface moisture

when inspecting areas where shadows occur, it is preferable to perform the inspection after sunset since during daylight hours the shadows move and can result in confusing test results



INFRARED TERMOGRAPHY Benefit

identification of superficial defects and areas containing humidity

interface analysis of FRP laminates externally bonded to RC beams \rightarrow






On site tests on existing structures: the knowledge process

INFRARED TERMOGRAPHY

Advantages

- □ Fast and detailed for great areas
- Usable also for unreachable structure
- □ Usable also during night-time Damp Patch

Disadvantges

- Results dependent from environmental conditions
- Results dependent from the emissivity of different materials







<u>RADAR</u>

Principle: based on the propagation of **electromagnetic energy** through materials of different dielectric constants \rightarrow the greater the difference between dielectric constants at an interface between two materials, the greater the amount of electromagnetic **energy reflected** at the interface







<u>RADAR</u>

Testing procedure

- ullet utilize 1 \div 1.5 GHz radar wave, against structure, and register the return signal
- □ high frequency give accurate tests, while low frequencies (100-500 MHz), increase the depth of penetration

Depth (m)	Centre Frequency (MHz)
0.3 - 0.5	1500
0.5 - 1	1000
1-2	500
2+	200
7.0	100



RADAR

Accuracy and interpretation

- □ hyperbolic shapes typically represent a point reflector
- the diameter of cylindrical objects ranging from rebars
 to metallic oil drums cannot be determined from
 radargrams
- radar wave velocity reduces and are more rapidly attenuated when travelling through wet concrete
- radar waves cannot penetrate conductors such as: metals, clays, salt water, e.g. sea water



(a)

(b)





<u>RADAR</u>

Advantages

- □ is free of the restriction of ambient conditions
- homogeneity of the concrete
- detecting localized loss of bond between the overlay and the concrete
- detecting delaminations in the concrete
- □ depth, spacing and omission of reinforcing steel

<u>Disadvantages</u>

- □ difficulty to interpret the signals
- □ reliant on the experience of the operator
- □ radar waves cannot penetrate conductors



RESISTIVITY MEASUREMENT

<u>**Principle</u>**: the ability of corrosion currents to flow through the concrete can be assessed in terms of the electrolytic resistivity of the material \rightarrow this resistivity can determine the rate of corrosion once reinforcement is no longer passive</u>



Apparent resistivity

Resistivity (ohm cm)	Likely Corrosion Rate
Less than 5,000	Very high
5,000 - 10,000	High
10,000 - 20,000	Low / Moderate
Greater than 20,000	Negligible



RESISTIVITY MEASUREMENT

Advantages

- □ The test give almost exact results to quantify rebar corrosion
- in general terms, where the resistivity is low, the probability of corrosion of the bars is higher, and vice versa

Disadvantages

- the presence of steel reinforcement close to the measurement location,
 surface layers due to carbonation or surface wetting can cause will cause an
 underestimate in the assessment of concrete resistivity
- measurements on a very small member section or close to a section edge may result in an overestimate of the resistivity
- measurements will fluctuate with changes in ambient temperature and with rainfall





The characterization of mechanical properties of soils could be determined through tests performed in different locations and for different goals:





PILES AND SOIL TESTING

- Quality control procedures shall be supplemented with an extensive range of pile and in situ soil testing. These can be grouped as static, dynamic and in situ testing.
- STATIC TESTING are employed determines the relationship between load and settlement, or to verify that the capacity of a pile exceeds the specified load. The constant rate of penetration technique can determine ultimate pile bearing capacity.
 - o Tension pile method
 - o Kentledge
 - o Anchor stressing



- DYNAMIC TESTING is an economical alternative to conventional static load testing, eliminating the need for costly proof loading. Integrity testing economically and reliably determines pile concrete and section uniformity.
- o Dynamic load testing
- Integrity testing
- IN SITU TESTING SOIL TESTING provides an accurate appraisal of the soil mechanics parameters used in the pile design, and is particularly useful where only limited site investigation data is available.
 - o S.P.T
 - o Cohesion strength
 - o Moisture content
 - o Plasticity and heave analysis
 - o Soil mineralogy



EDOMETRIC TEST



Edometric setup





Triaxial apparatus and setup



INVESTIGATION METHODOLOGIES AND TECHNIQUES

SHEAR TEST



- The mechanical properties of soils are determined on laboratory tests typically through specimens obtained from boring.
- The reliability of results is strictly related to the disturbance degree during boring and transportation.
- □ For these reasons in situ tests are needed also because they assess the mechanical characteristic directly on soil.





Gathering and storage of specimens



By comparing different analyses and borehole logs in different positions a three dimensional restitution is possible. This allows to understand a possible development of soil.







Scrovegni's chapel, Padova Inside the chapel there are Giotto's frescoes



CONE PENETRATION TEST

The CPT is a static penetration test where the cone is pushed into the soil with average speed of 2 cm/sec). The cone has a base area of approximately 10 square centimeters. The cone could have also further functions:

- o CPTU That measures also the water pressure thus also the overpressure inside cohesive soils
- **SCPT** That measures the waves generated by an instrumented hammer to characterize the velocity of shear waves.

Instead another test is the SPT where the instrument is driven into the soil and it is measured the number of shots.





Dynamic behaviour and waves velocity

There are many types of tests:

- ON THE SURFACE
- o INTO THE SOIL

ON THE SURFACE

- Methodology: The test is based on studying different velocities of seismic waves that are related to different type of soils using refracted wave measured by accelerometers on the surface.
- **Supplementary methods:** These tests are useful in ground investigation but for a correct interpretation they require direct tests too (e.g. boring).

INTO THE SOIL

• Methodology: The test is based on studying different velocities of seismic waves using the source or the receiver inside bore or in some case both of them into the bore.







SHM: INTRODUCTION

- Needs for an effective seismic protection and vulnerability reduction of infrastructures, strategic structures and Cultural Heritage (CH) buildings;
- Historic buildings, due to their structural features, construction techniques and used materials, are particularly vulnerable to earthquake actions;



STRUCTURAL HEALTH MONITORING (SHM) a measure of passive mitigation of earthquake effects

- Continuous or short/medium-term controls of quantities related to the structural behavior and connected to the evaluation of their evolution with the passing of time;
- Large number of applications in the field of civil engineering such as: design, damage detection and assessment, maintenance and retrofitting of existing structures, structural control during earthquakes (using semi-active systems).





MONITORING TECHNIQUES



STATIC

- Measurement of static timedependent parameters that vary slowly
- Controls of: crack pattern, activation of collapse mechanisms, state of stress and strain, variation of environmental parameters, ...
- Local controls and damage identification





DYNAMIC

- Measurements of ambient vibrations or exceptional events (e.g. earthquakes)
- Identification of dynamic timedependent parameters (modal parameters)
- Continuous, trigger-based or punctual
- Global controls and damage identification







Structural problems vs. monitoring strategy

Location: substructure

Observation: settlements

Related problems: Monitoring strategy: Monitored entity-ies: Technology: cracks opening, tilting of tall structures, control of settlements & environmental distance, environment borehole extensometers, telemetry (level), T and RH sensors, piezometers (water table level)...







T-RH sensor



Structural problems vs. monitoring strategy

Location: substructure

Observation: settlements

Settlements of the structure can be measured related to reference points, by means of telemetry (i.e. levels), or in terms of settlements on the underlying soil, at different depths (rod extensometers)





Application of SHM to Cultural Heritage structures





Application of SHM

ROLE OF MONITORING

- INVESTIGATION PHASE
- INTERVENTION PHASE
- **EVALUATION PHASE**
- Maintenance Phase
- i. INVESTIGATION
- Dynamic characterization
- Model updating
- Damage Identification
- Emergency actions

ii. EXECUTION

- Structural controls before, during and after the execution
- Incremental approach and sequential interventions





iii. Evaluation

Assessment of interventions' influence on the structural response

- Assessment of interventions' effectiveness
- Evaluation of possible upgrading solutions

iii. Maintenance

- □ Long-term monitoring program
- Assessment of long-term effectivness and durability of interventions
- Quality control plans, maintenence works and corrective measures



10. Application of SHM to bridges

Ponte Nuovo del Popolo - Verona

Three-span concrete bridge: total length 90.5 m, central span 33.5 m, side spans 27.5 m. 4 lanes and 2 sidewalks for a width of deck equal to 14.45m. Original bridge of 1179, destroyed 6 times. The current bridge dates back to 1946.









RESPONSE TO STATIC AND DYNAMIC ACTIONS



LIMITS OF THE EXISTING TOOLS FOR THE ANALYSIS OF STRUCTURAL RESPONSE TO STATIC AND DYNAMIC ACTIONS



Università degli Studi di Padova



Spostamenti relativi monitorati dal sensore PZ01 e PZ02 PZ01

DEGLI STUDI

DI PADOVA

Static Monitoring



0.3

LIMITS OF THE EXISTING TOOLS FOR THE ANALYSIS OF STRUCTURAS^{postamenti raffrontati con la tem} RESPONSE TO STATIC AND DYNAMIC ACTIONS

Seismic events registered by INGV INGV Peak Velocity Map (in cm/s) : Pianura_padana_emiliana MAY 20 2012 02:03:53 AM GMT M 5.9 N44.89 E11.23 Depth: 6.3km ID:8222913230 Monitoring of the seismic event(20/05/2012) 45. Accelerometer 1, 2012/05/20-03:02:20 Acc.[m/s²] 45 10 50 20 40 60 0 30 Accelerometer 2 44. Acc.[m/s²] 0 10 20 30 40 50 60 11' 12" Accelerometer 3 012 08-44-21 AM ON 0.5 Acc.[m/s²] Accelerometers 1-6, 2012/06/03-19:19:40 0.1 ويروع وفقا يتفرأن أفألتهم وليروأه and started a little produced. 0.08 -0.5 50 0 10 20 30 40 60 0.06 Accelerometer 5 Acc.[m/s²] 0.04 0.02 Acc.[m/s²] -1 -0 10 20 30 40 50 60 -0.02 **Peak on the Bridge** Amplification factor on the **PGA** -0.04 $[m/s^2]$ [m/s²] Bridge -0.06 0,074 0,84 11,35 -0.08 -0,82 -0,070 11,71 10 20 30 40 50 60 e [sec]

LIMITS OF THE EXISTING TOOLS FOR THE ANALYSIS OF STRUCTURAL RESPONSE TO STATIC AND DYNAMIC ACTIONS

Università degli Studi di Padova



Thanks for your attention!

claudio.modena@dicea.unipd.it

Department of Civil, Environmental and Architectural Engineering

www.smingegneria.it

claudio.modena@smingegneria.it



















ועדת ההיגוי הבין-משרדית להיערכות לרעידות אדמה National Steering Committee for Earthquake Preparedness

